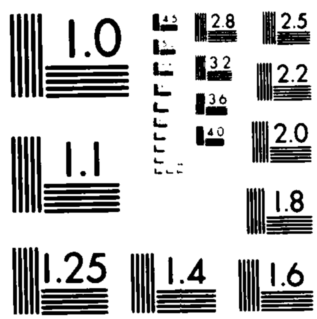

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THERMAL ENERGY STORAGE EVALUATION AND LIFE TESTING

Robert Richter
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January 1983

Interim Report for Period May 1981 - October 1981

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This technical report has been reviewed and is approved for publication.

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Two thermal energy storage (TES) units which were built under a previous contract were tested with a Hi-Cap Vuilleumier cryogenic cooler in the facility of the Hughes Aircraft Corporation. The objective of the program was the evaluation of the behavior of the TES units as well as the determination of the temperature history of the three cold stages of the Vuilleumier cryogenic cooler during cyclic charging and discharging of the TES units. The test results have confirmed that thermal energy storage can provide the necessary thermal power

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to the hot cylinders of the Vuilleumier cryogenic cooler at the required operating temperature. Thereby the continuous cooling capability of the cooler during an eclipse when no electrical power is available is being assured. The cold stage temperature amplitudes during a complete charge - discharge cycle of the TES units were only about 10% of the amplitudes which were observed when the Hi-Cap Vuilleumier cryogenic cooler was operating without thermal energy storage backup in a simulated orbit of 54 minutes sun exposure and 18 minutes eclipse time. The thermal conductivity of the molten thermal energy storage salt was apparently only a fraction of the thermal conductivity which had been assumed for the prediction of the upper heater temperatures. A redesign of the heater configuration is indicated to permit the charging of the TES unit with maximum temperatures below 1480°F which is now required for full charging of the TES units within 54 minutes with the present heater design.

FOREWORD

The information presented in this report was generated during the performance of the task "TES Test Support for HAC Thermal Energy Storage Unit Evaluation and Life Testing". The task was sponsored by the Air Force under Task SD2126 and Space Division Aero Propulsion Laboratory, Work Unit 31451949. The technical work was carried out by the Advanced Technology and Applications Group of the Control and Energy Conversion Division (340) at the Jet Propulsion Laboratory of the California Institute of Technology, Pasadena, California.

Robert Richter was the principal investigator of the program. This is an interim report which presents the test results which were generated during the performance testing of TES units #1 and #2. The program was sponsored by the Systems Division of the Air Force with Dr. E. T. Mahefkey of the Aero Propulsion Laboratory (AFWL/POOC) acting as technical monitor. The work was performed during the period of 1 May 1981 to 31 October 1981 with the draft report submitted in November 1981.

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SECTION I

INTRODUCTION

This program had as its objective the testing of two thermal energy storage units with a Hi-Cap Vuilleumier cryogenic cooler in the configuration as shown in Figure 1. The two thermal energy storage (TES) units which were built consecutively under Air Force sponsorship, Contract F33615-75-C-2045, are described in References 1 and 2.

The specifications for the two thermal energy storage units were established from mission analyses and Vuilleumier cryogenic cooler requirements which were current at the time of the initiation of the design of the first of the two TES units. The design and construction of the second TES unit was initiated after the first TES unit had been tested and the achievement of the two major design goals had been confirmed, the desired thermal energy storage capacity was achieved within the maximum allowable temperature variation during discharge. Each TES unit was designed to supply 650W of thermal power for 18 minutes to one of the two hot cylinders of the Hi-Cap Vuilleumier cryogenic cooler. One goal was also to limit the thermal losses from the thermal energy storage unit to less than 5 percent of the design output power, i.e., 32.5 W. Furthermore, the stored energy was to be released with a temperature differential which would maintain the operating temperature of the hot cylinders within the range of 1225°F to 1275°F. Based on the specified design goals, the thermal energy storage unit had to be configured for a total thermal energy storage capacity of 7.371×10^5 J that could be released over a temperature range of 50°F.

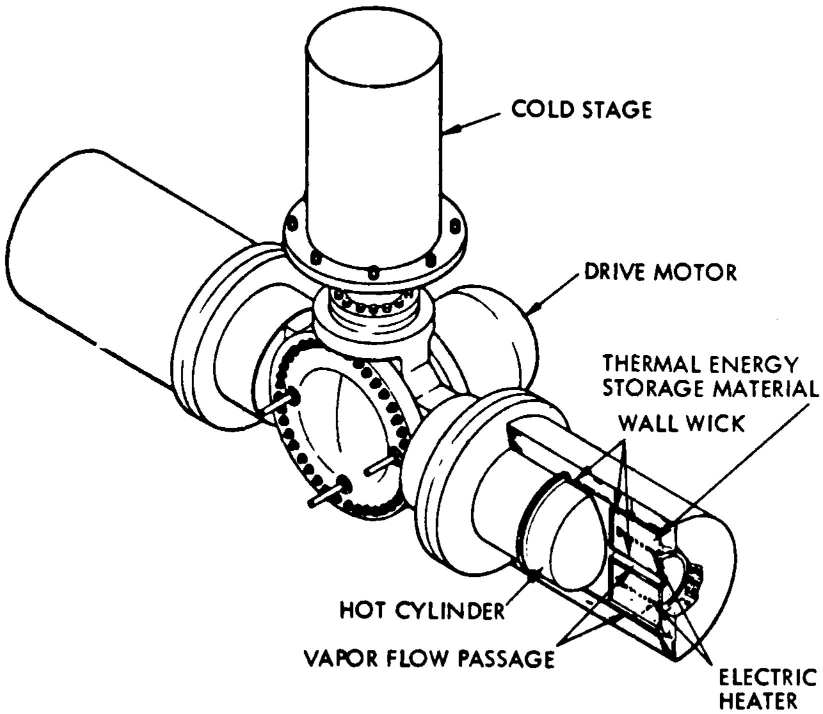

Figure 1. Hi-Cap Vuilleumier Cryogenic Cooler with Thermal Energy Storage Units

SECTION II

TEST SETUP

2.1 THERMAL ENERGY STORAGE UNITS

Though the specifications for the two thermal energy storage units remained the same, minor variations in the construction of the two units existed. The primary differences which affected the operation and the testing of the two TES units are associated with the heater elements and the temperature sensors.

The first thermal energy storage unit contains eight heater elements whose average hot resistance is 42.67 ohms, while the second unit incorporates heater elements with an average hot resistance of only 39.80 ohms. This variation in the electrical characteristic of the two TES units was imposed on the program by the inability of the heater element supplier to duplicate the heater element values after a manufacturing interval of approximately 18 months. When the two TES units are connected in parallel to the same electrical power source, the units draw considerably different power and thus are being charged at different rates.

The first thermal energy storage unit is equipped with three temperature sensors, two K calibration thermocouples and one platinum Resistance Temperature Detector (RTD). At the initiation of the TES program, the intention was to instrument the unit with three RTDs, as the final user of the thermal energy storage units had indicated that the control circuitry was to be designed for an RTD signal input. For the initial performance testing of TES unit #1 during the TES unit development program the unit was insulated with Flexible Min-K insulation. This insulation afforded easy application and removal whenever the repair or replacement of a heater element or temperature sensor was required. Several RTDs failed after only a few cycles of heating and cooling, and were replaced repeatedly. Finally, K calibration (Chromel-Alumel) thermocouples were substituted for all non-operational RTDs.

The initial performance testing was conducted with one RTD still functional. This temperature sensor remained in place when the thermal energy storage was insulated with the superinsulation for its final assembly. However, this sensor also failed during the final performance testing and could not be replaced with

a thermocouple as this would have meant the removal and reapplication of the superinsulation, a task which would have been too costly.

Thus, at the start of this program the first thermal energy storage unit was instrumented with only two temperature sensors, one sensor located in the area of the heater element and the other on the skirt of the thermal energy storage unit which surrounds the hot cylinder. The second thermal energy storage unit was instrumented with three K calibration thermocouples, two located in the area of the heater and the third on the skirt as shown in Figure 2. The placement of the superinsulation was refined for lowering the thermal losses to the desired value of 5% of the total thermal power requirement, i.e., 34.13 watts.

2.2 POWER AND CONTROL REQUIREMENTS FOR THERMAL ENERGY STORAGE UNITS

For the operation of the two thermal energy storage units the electrical power input and a control logic was established. Each thermal energy storage unit required a minimum electric power input of 910 watts for the duration of 54 minutes to achieve a full thermal charge while concurrently supplying 682.5 watts of thermal power for the operation of the Vuilleumier cryogenic cooler. To assure the attainment of a full charge within 54 minutes the power input at the initiation of the charging cycle following a complete discharge was to be approximately 10% higher than the minimum charging power, i.e., about 1,000 watts. The preferred initial charging power would have been even higher, an operating condition which was expected to be established by test data during the test program.

The state of charge of the TES units was to be determined by the rate of change of the temperatures during the charge and discharge periods as indicated by the thermocouples. The attainment of the full charge of the TES units would be confirmed by a distinct change in the rate of the temperature rise occurring during charging at constant power input. The temperature at which this rate change occurs is the breakout temperature which has a distinct value for a given power input. The change in the temperature slope would indicate that thermal energy is no longer absorbed in the form of latent heat of fus: n, i.e., phase change energy, of the TES material. When the indicated temperature exceeds the breakout temperature by 5 to 10°F the total input power could be reduced to the power demand of the Vuilleumier cryogenic cooler. Under these conditions the

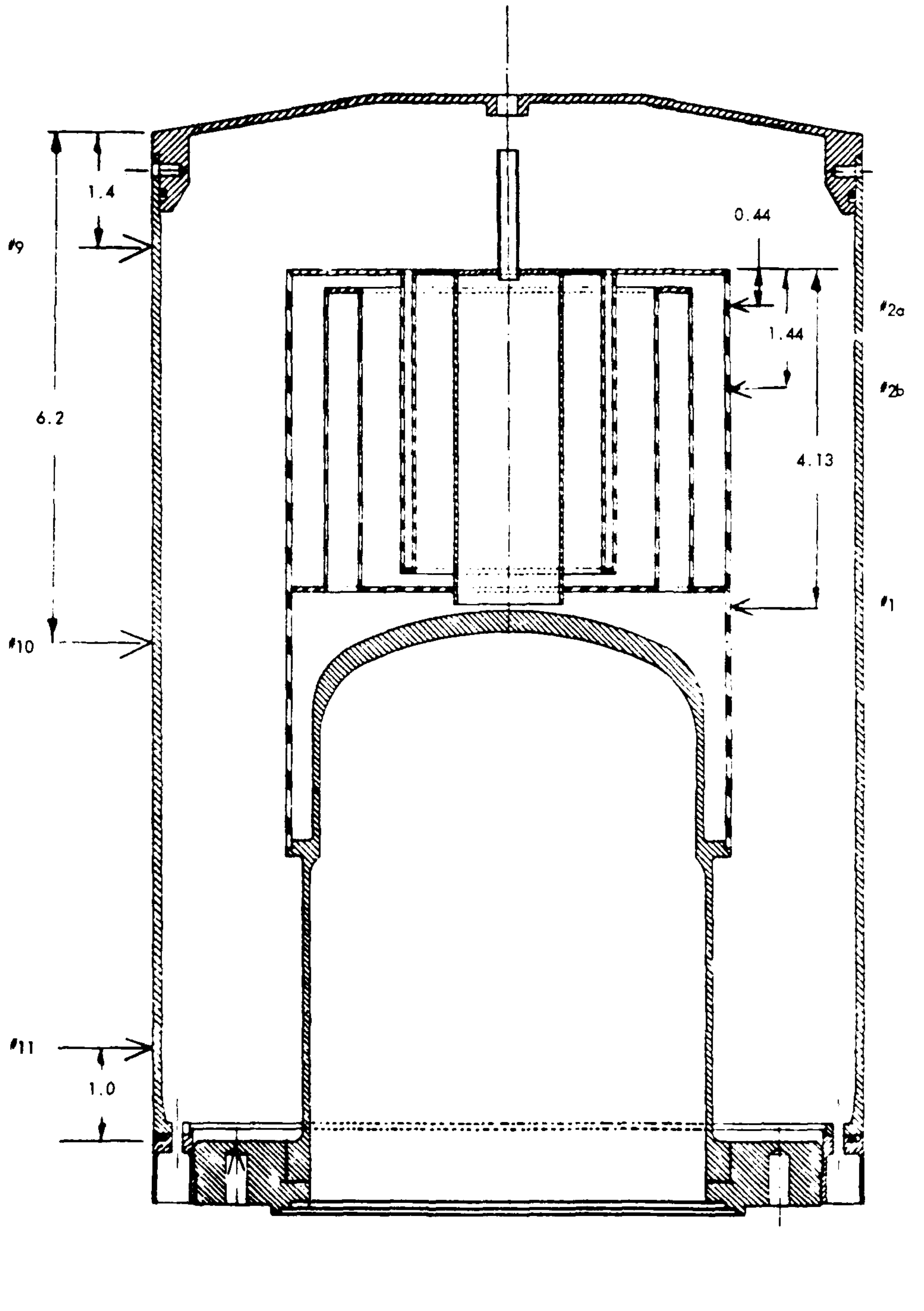

Figure 2. Thermocouple Locations on Thermal Energy Storage Units

TES units would remain fully charged, while thermal power is supplied to the Vuilleumier cryogenic cooler from the heaters by conduction across the molten TES material. This preferred power control logic for a Vuilleumier cryogenic cooler with thermal energy storage backup is quite different from the power control logic which is employed for maintaining the temperature of the hot cylinder with electrical heaters which are mounted directly on the hot cylinder outer surface. In this purely electrically powered configuration of the Vuilleumier cryogenic cooler the temperature as sensed by a thermocouple is maintained by controlling the voltage input. Because considerable experience had been gained for this type of power control, the power control for the TES units was designed following the same principle.

The disadvantage of controlling the power input by a fixed temperature becomes obvious. During charging of the TES unit the heater temperature has to increase constantly with increasing charge, i.e., with increasing amount of thermal energy storage material having changed from the solid state into the molten state. When the entire thermal energy storage material has been liquified the electric power input into the unit can be reduced to the level as determined by the power requirement of the Vuilleumier cryogenic cooler when operating at a desired performance level. Since after full charging has been achieved less power needs to be transferred from the outer diameter of the TES unit to the inner diameter of the thermal energy storage, the heater temperature can be permitted to decrease at the end of the charging cycle, while the hot cylinder temperature will remain constant. This temperature profile can be attained by charging the thermal energy storage unit at a fixed power input and reducing the power input to the Vuilleumier cooler power requirement after achieving full charging as indicated by the distinct change in temperature rise.

The control of the upper temperature prevents the arrest of the hot cylinder temperature at the end of the charging cycle. This causes a continuous increase in the power input into the hot cylinder. Since the hot cylinder temperature is the major parameter which determines the temperatures of the three cold stages of the Vuilleumier cooler, a corresponding further decrease in their temperatures occurs.

Based on the above described operating characteristics of the Vuilleumier cryogenic cooler and the TES unit, a control logic that adjusts the power input from the charging power level to the Vuilleumier cryogenic cooler demand power level after the thermal energy storage has been achieved full charge is preferable over a control logic that maintains an upper heater temperature which is required purely for charging. A power controlling logic can therefore maintain the cold temperatures within a narrower band than the temperature controlling logic by holding the hot cylinder near the melting temperature of the thermal energy storage material at the end of the charging cycle. In the power controlling logic furthermore the upper temperature of the heaters is being reduced immediately upon reaching full charge. Thereby the exposure of the heaters to the highest operating temperature has been reduced to a smaller fraction of the total operating time.

2.3 GENERAL TEST SETUP

The two thermal energy storage units described in References 1 and 2 were mounted on a Hi-Cap Vuilleumier cryogenic cooler as shown in Figure 1. The components were found to be fully compatible, though the Vuilleumier cryogenic cooler was built by the Hughes Aircraft Corporation and the thermal energy storage units had been supplied by the Xerox Corporation. When the volumes of the thermal energy storage units which contain the heater elements and the thermal insulation was evacuated the outer aluminum container of Unit #1 was found to be no longer vacuum tight. Vacuum tightness of the TES container is only required when the Vuilleumier cryogenic cooler is operated in the earth atmosphere in order to maintain the low heat transfer high insulation capability of the superinsulation and thereby minimizing the thermal losses from the thermal energy storage unit. Vacuum was maintained by continuously operating a small vacuum pump which remained connected to the thermal energy storage units during all tests. Three additional thermocouples were located on the outside of each thermal energy storage unit as shown in Figure 2 for monitoring the effectiveness of the insulation.

All thermocouples were connected to a datalogger, Fluke 2240B. This permitted the direct printout of the measured temperatures in the Fahrenheit scale with all the other data which were monitored by the datalogger. The output of thermocouples #2, i.e., the thermocouples which are located in the area of the heater,

was also processed as an input to the temperature controllers' differential amplifiers. The measured correlations of the processed voltages and the indicated temperatures are shown in Figure 3.

All eight heater elements of each of the two thermal energy storage units were connected in parallel. The total resistance of each thermal energy storage unit as seen by the power supply was therefore one eighth of the resistance of one heater element, i.e., about 5 ohm. Each unit was connected to its own power supply circuit whose total resistance was controlled by the respective temperature controller. The power supply received its power from a 100 volt dc power source which also supplied the electrical power for the Vuilleumier cooler motor and all other components which require electrical power, as for instance, the control circuit of the temperature controllers.

2.4 TEST REQUIREMENTS

Prior to the initiation of the testing of the thermal energy storage units the power requirements and the upper operating temperatures were determined.

2.4.1 POWER REQUIREMENTS

The thermal energy storage units had been designed for a thermal power capacity of 682.5 watt for 18 minutes. Recharging of the thermal energy storage units after full discharge, i.e., extraction of all latent heat of fusion of the thermal energy storage material, was to be achieved within 54 minutes. The minimum total electric power input is therefore 910 watt.

2.4.2 CONTROL TEMPERATURE SETTING

The upper operating temperature occurring at the outer surface of the thermal energy storage unit was calculated to be 1358°F at the end of the charging cycle. This temperature was based on the assumption that the thermal conductivity of the molten TES material was equal to the thermal conductivity of the solid material. Some reported test data had even indicated that the thermal conductivity of the molten salt could be considerably lower than that of the solid salt. The temperature control unit was therefore designed for a control temperature of around 1360°F, which could be adjusted during the initial testing to reflect the actual upper temperature needed for assuring complete charging of the TES unit.

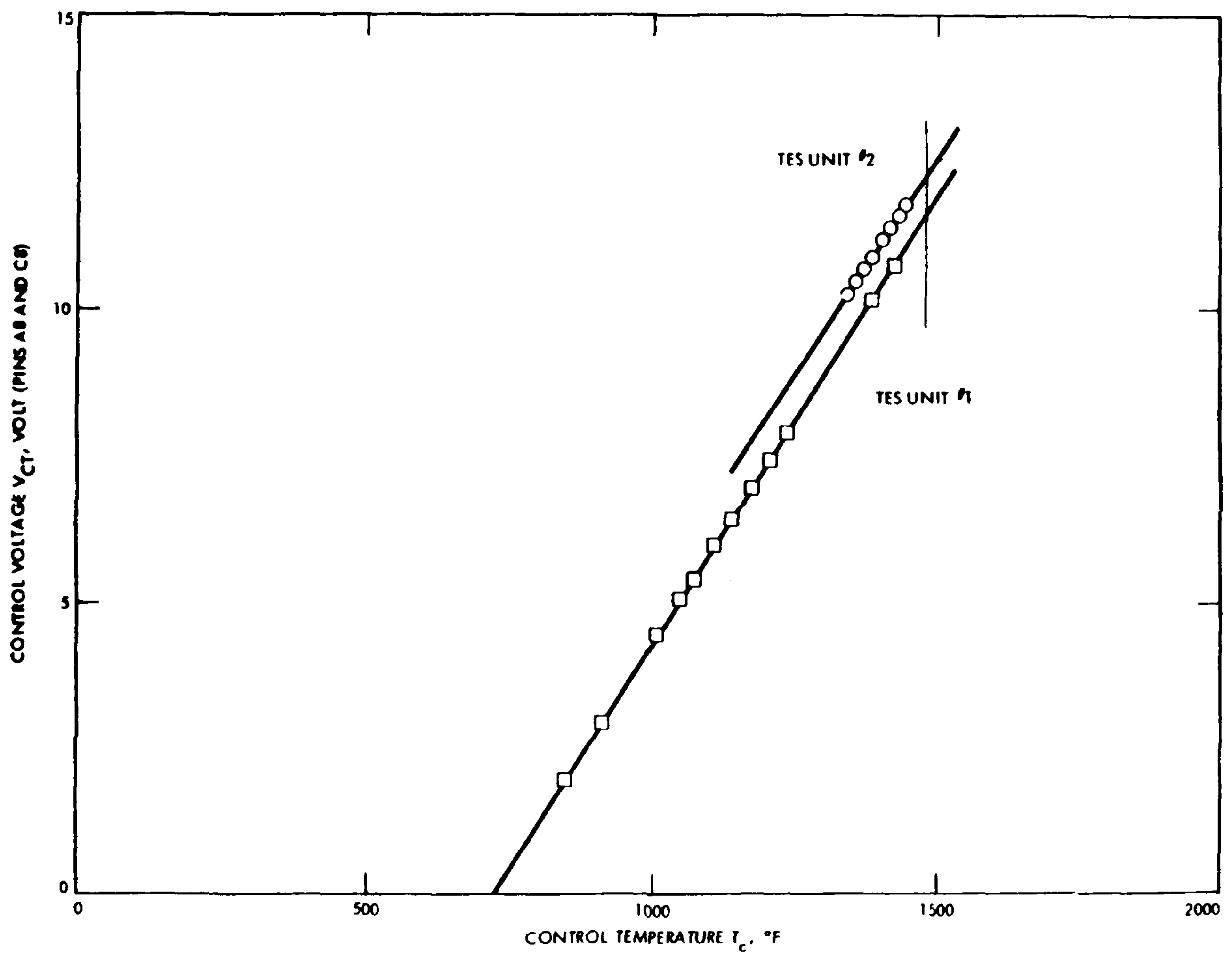

Figure 3 Correlation Between Control Voltage and Control Temperature

SECTION III

TESTING

3.1 TEST INITIATION

3.1.1 POWER SUPPLY AND TEMPERATURE CONTROL

Testing of the combined Vuilleumier cryogenic cooler with two thermal energy storage units was initiated with the intent of producing solely the data points which were laid out in the test plan (Ref. 3). However, a considerable amount of preliminary operation was required for the evaluation and adjustment of the new power supply and control instrumentation. Initially a power input of only 867 watt and 929 watt for TES unit #1 and TES unit #2 respectively could be achieved because the power supply was limited to a maximum voltage of only 68 volt. By minor modifications in the power supply the maximum available voltage was raised from 68 volt to 72 volt. This increased the maximum power available for TES unit #1 and TES unit #2 to 972 watt and 1042 respectively. Any further increase in the available power would have required major modifications in the controlled power supply.

The temperature controller was designed for a relatively limited temperature range and needed modifications to extend the temperature range as well as to decrease the power excursions after initiation of control over the power supply.

3.1.2 THERMAL ENERGY STORAGE UNITS

The initial test data indicated that the control temperatures which were the temperatures on the outside of the thermal energy storage units had to be set considerably higher than had been anticipated for achieving full charge of the TES units. The effective thermal conductivity of the thermal energy storage material in the molten state appeared to be only a fraction of what had been anticipated. Materials data for salts were discovered in recent literature (Ref. 4) which indicated that molten single fluoride salts exhibit thermal conductivities which are approximately only 25% of those of the solid salt. No thermal conductivity data for the particular eutectic ternary salt which is being used in the thermal energy storage units could be located. When the molten material for a thermal conductivity of only k_L = 0.00743 watt/cm-K was assumed, i.e., 25% of k_s, a control temperature of 1498°F was calculated with a

new computer analysis. The range of the temperature controller had therefore to be extended to cover the newly determined control temperature setting.

3.1.3 TESTING

Testing was inhibited by the need to terminate operation entirely by the end of a working day. The Vuilleumier cryogenic cooler and the power to the TES units had to be turned off prior to leaving the test unit unattended during the night. This required the start up of the unit with the cold stages and the thermal energy storage material at room temperature at the start of each test.

3.2 PERFORMANCE TESTING

3.2.1 NO LOAD AT 190 RPM

Figures 4 and 5 present the measured temperatures and the input powers to TES units #1 and #2. Unit #1 was charged with a total power input of 972 watt. When the control temperature reached 1488°F the thermal control initiated a reduction in the input power in proportion to the need for maintaining a constant temperature. Full charging of the TES unit apparently was completed when thermocouple #1 indicated 1275°F. When this temperature was reached the total power requirement for the Vuilleumier cryogenic cooler and the thermal energy storage unit could have been reduced to the operating power of the Vuilleumier cooler which was 682.5 watt.

Because the power input was controlled by the upper temperature of the TES unit, it remained above the power requirement of the Vuilleumier cryogenic cooler. When the TES unit was fully charged with latent heat of fusion, further charging of the unit with sensible heat caused a rise in the operating temperature of the hot cylinder.

At the end of the charging period of 54 minutes the electrical power to the TES unit was turned off. At this time the hot cylinder temperature had reached 1338°F and was still rising. During the discharge period of 18 minutes the cooler operated for 9 minutes entirely on the sensible heat of the TES unit. Release of latent heat of fusion apparently started when TC #1 indicated a temperature of 1269°F. This temperature was about 6°F below the temperature which indicated the completion of the charging cycle of the TES unit with latent heat of fusion. After 18 minutes of operating the Vuilleumier cryogenic cooler on

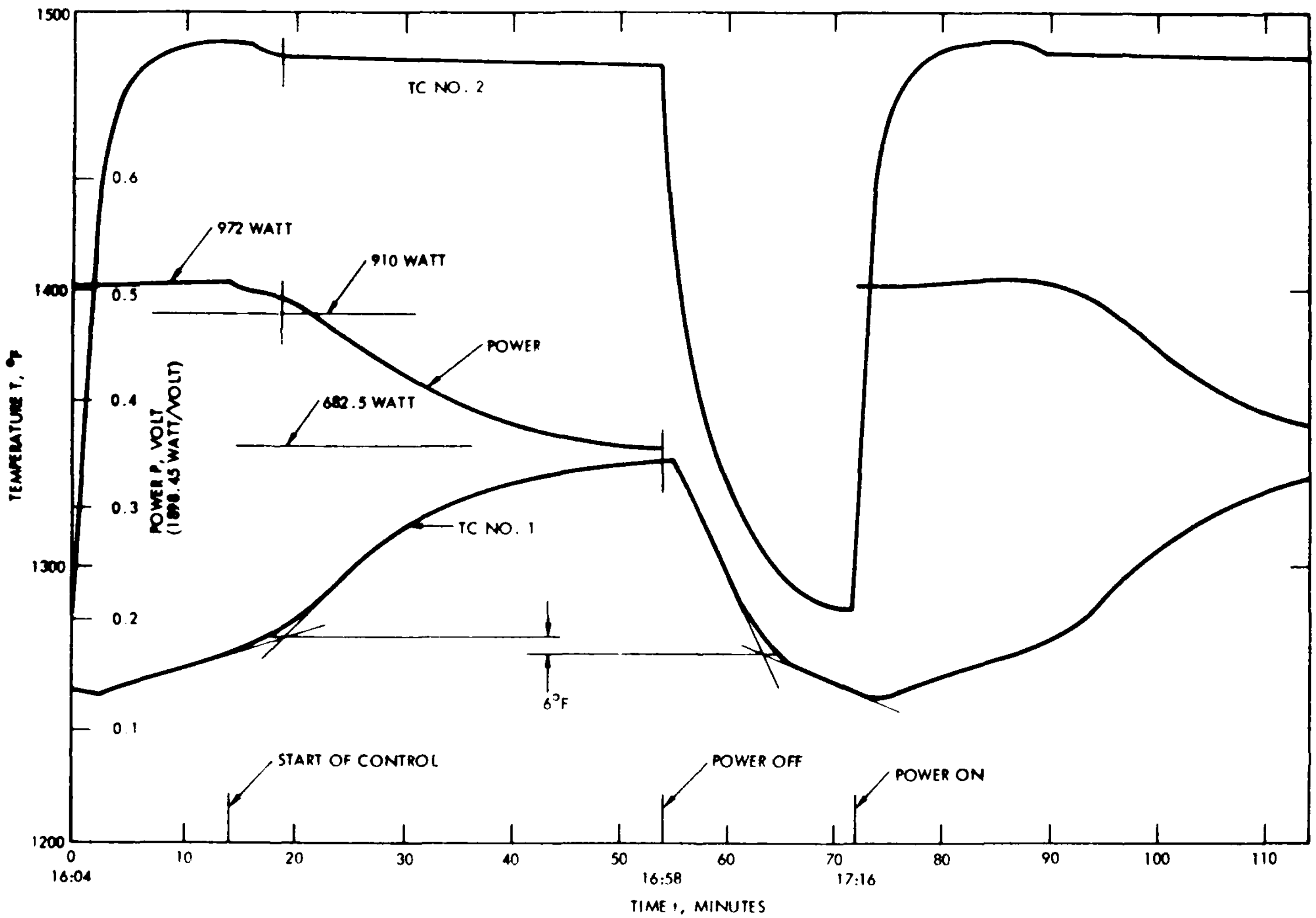

Figure 4 Thermal Energy Storage Cycling Test (Unit #1, No Load @ 190 RPM)

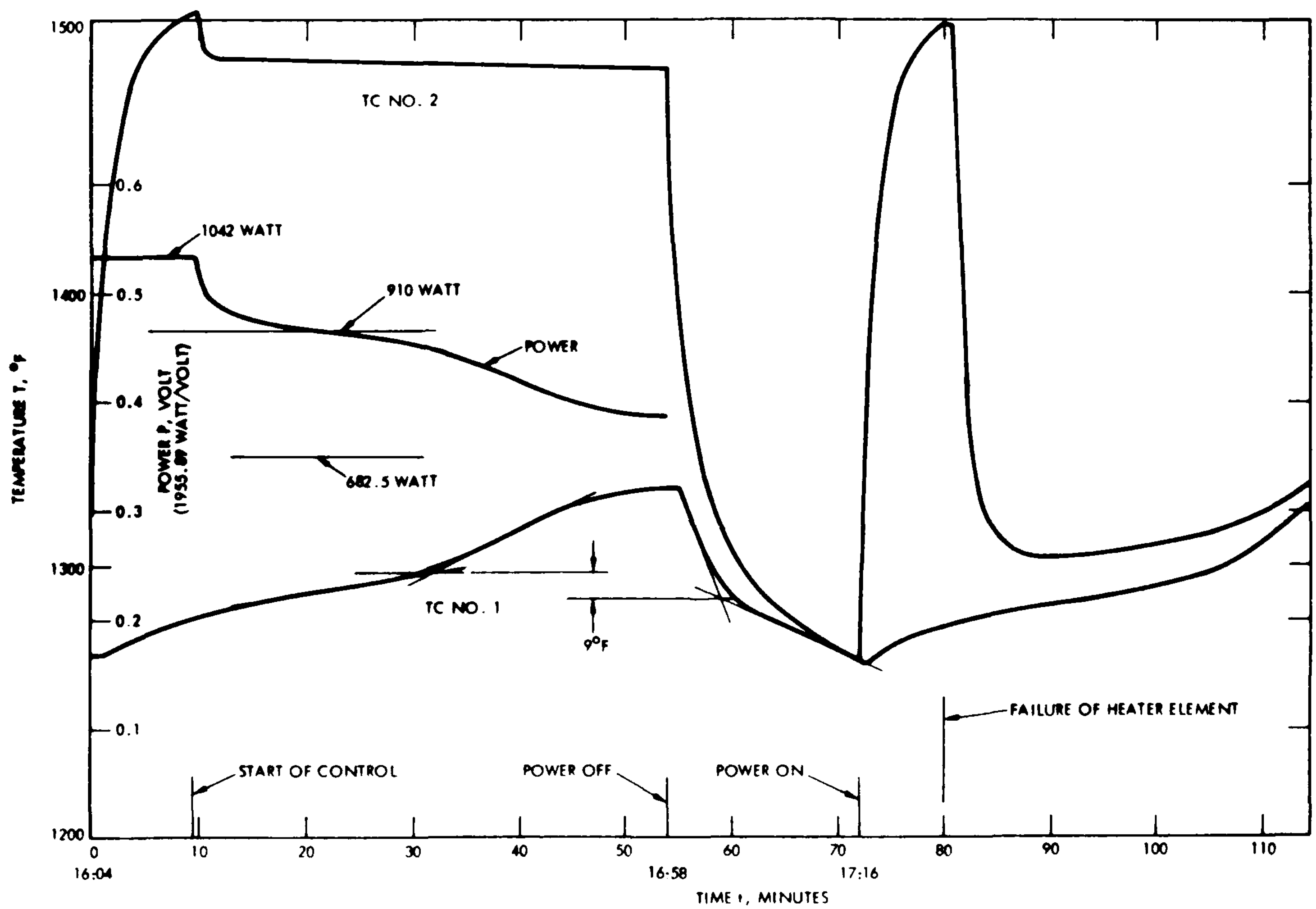

Figure 5 Thermal Energy Storage Cycling Test (Unit #2, No Load @ 190 RPM)

the sensible and latent heat of the TES unit full power was applied again to the TES units. During the discharge period the hot cylinder temperature ranged from a high of 1338°F to a low of 1252°F. If the discharge would have been initiated from a temperature at which the TES unit was solely charged with latent heat of fusion the temperature range would have been between a high of 1268°F and a low of 1236 °F as indicated in Figure 6 . During the recharge cycle the indicated hot cylinder temperature at which the thermal energy storage unit was fully charged was 1274°F which compares with 1275°F of the first charge cycle. During the following discharge the start of the release of latent heat was indicated at a hot cylinder temperature of 1268°F. This temperature varied only by 1°F from the indicated temperature of the first discharge cycle. This deviation is well within the accuracy with which these temperatures could be determined.

The behavior of TES unit #2 was quite similar to that of TES unit #1. Because thermocouple #1 of Unit #2 was made with a 1/16-inch sheath the indicated hot cylinder temperature was higher. The conclusion of the charging of the thermal energy storage unit was therefore indicated at T = 1297°F, which is closer to the actual melting temperature of the TES material. The initiation of extraction of latent heat of fusion was indicated at a hot cylinder temperature of 1286 °F. If the discharge period would have been initiated from this temperature, the hot cylinder temperature would have dropped to 1256°F at the end of 18 minutes. This would have resulted in a temperature variation of only 30 °F during the discharge period. This compared with a temperature range of 32 °F for TES unit #1.

The hot cylinder temperatures of the two units is compared in Figure 7 . When comparing the behavior of the two TES units the difference in the initial charging rates by 70 watt has to be taken into account. In Figure 6 the discharge characteristic of the two units is compared with the analytically predicted discharge temperature range. A temperature difference of 34°F is predicted by plotting the variation of the temperature which would be measured at the interface between the thermal energy storage material and the container wall. This compares with a temperature variation of 32°F and 30°F which were measured for the two units.

The temperatures of the cold stages are presented in Figures 8, 9 and 10. On the same graphs the cold stage temperatures as measured during the cyclic operation

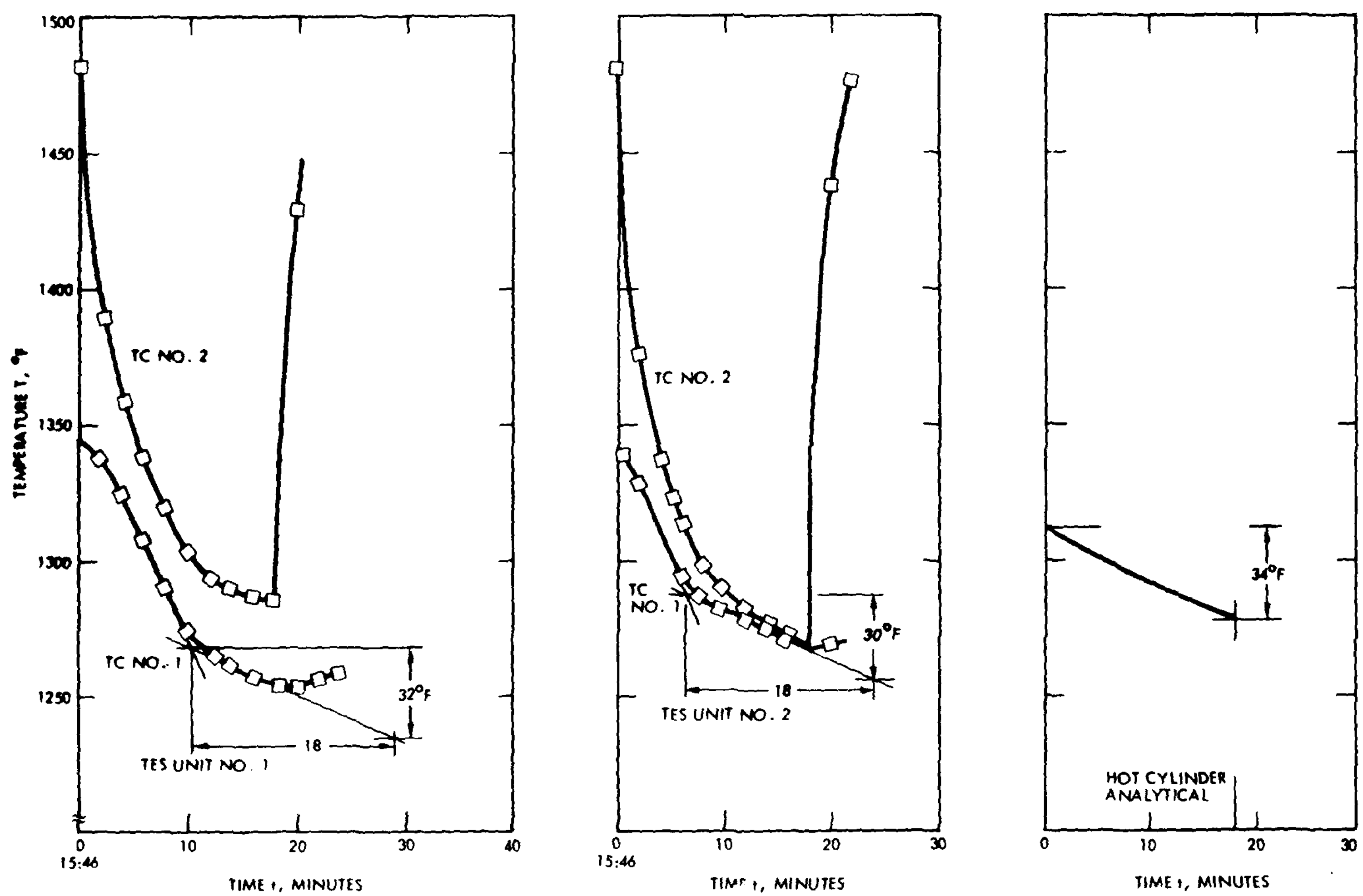

Figure 6 Discharge Cycle of Thermal Energy Storage Units #1 and #2

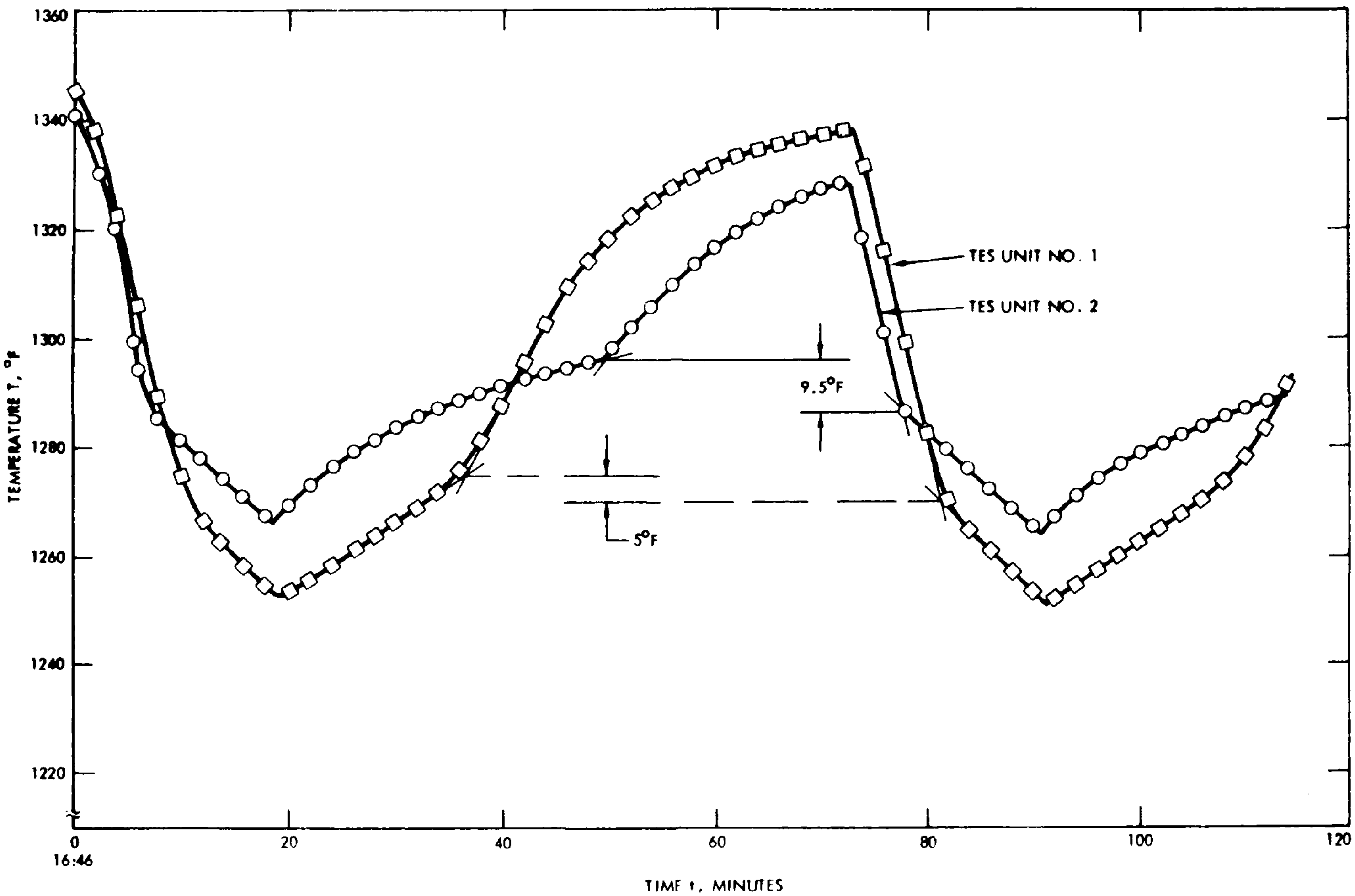

Figure 7 Indicated Hot Cylinder Temperature During Cycling Test (No Load @ 190 RPM)

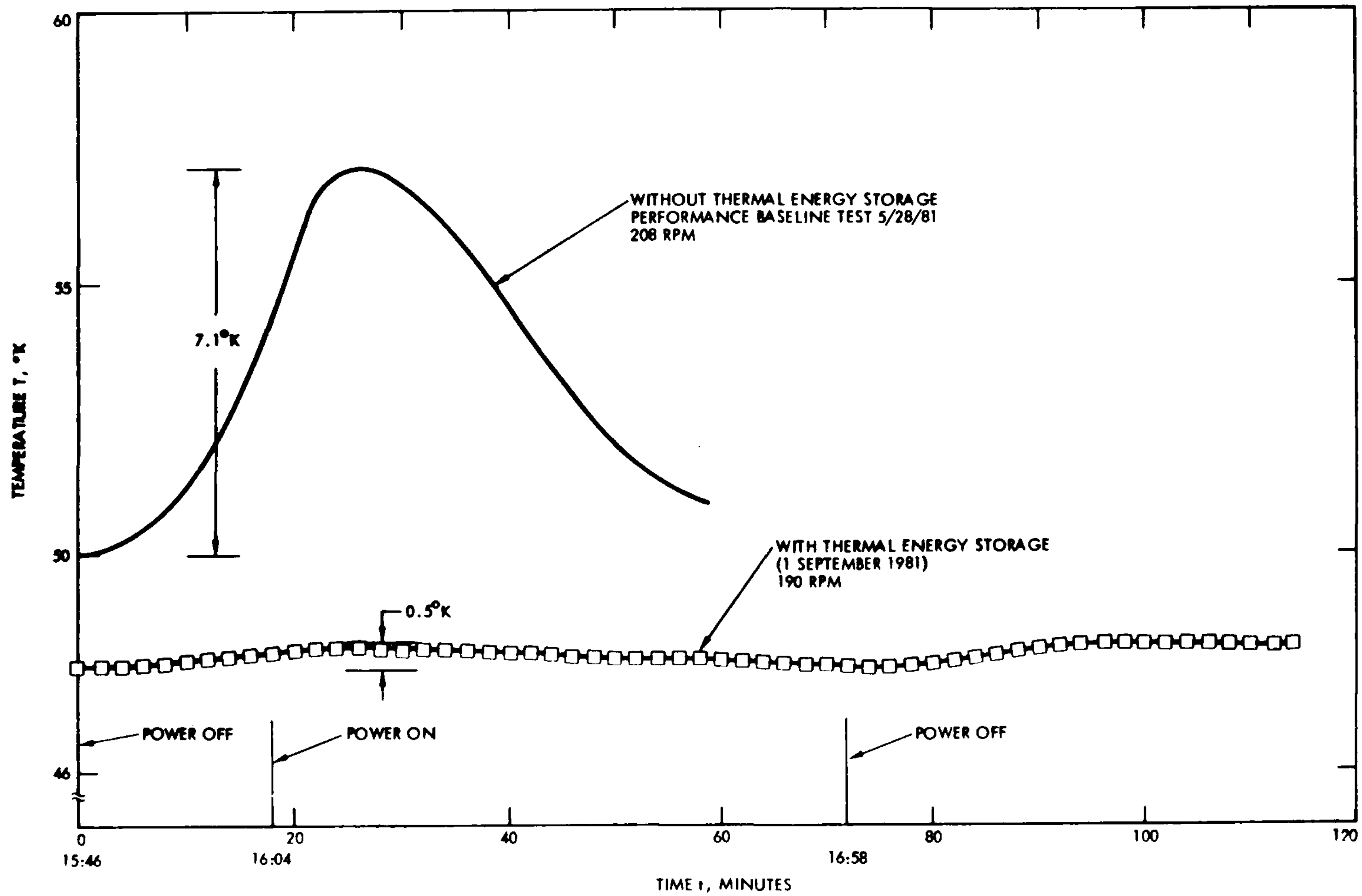

Figure 8 First Cold Stage Temperature During Discharge and Charge (No Load @ 190 RPM)

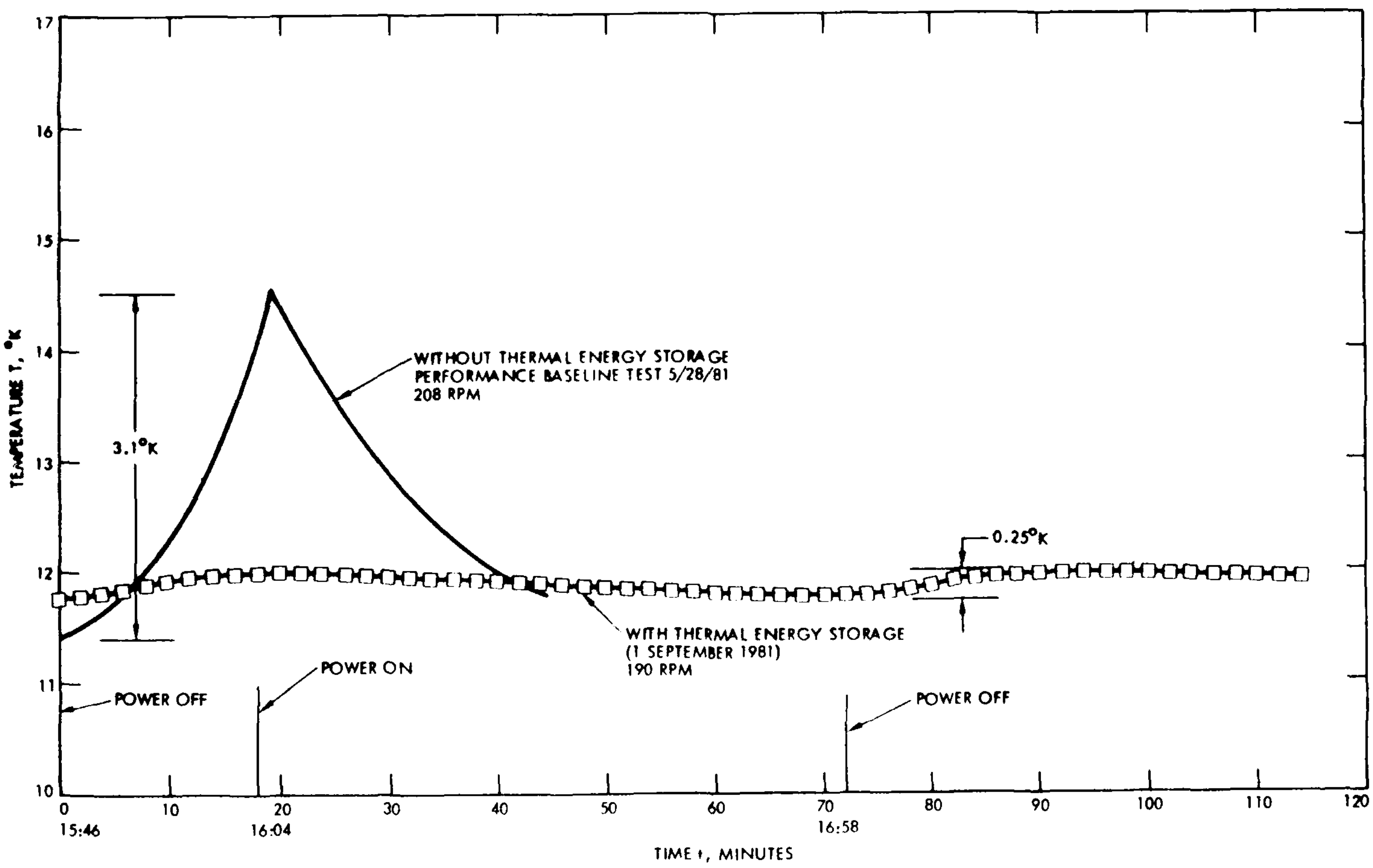

Figure 9 Second Cold Stage Temperature During Discharge and Charge (No Load @ 190 RPM)

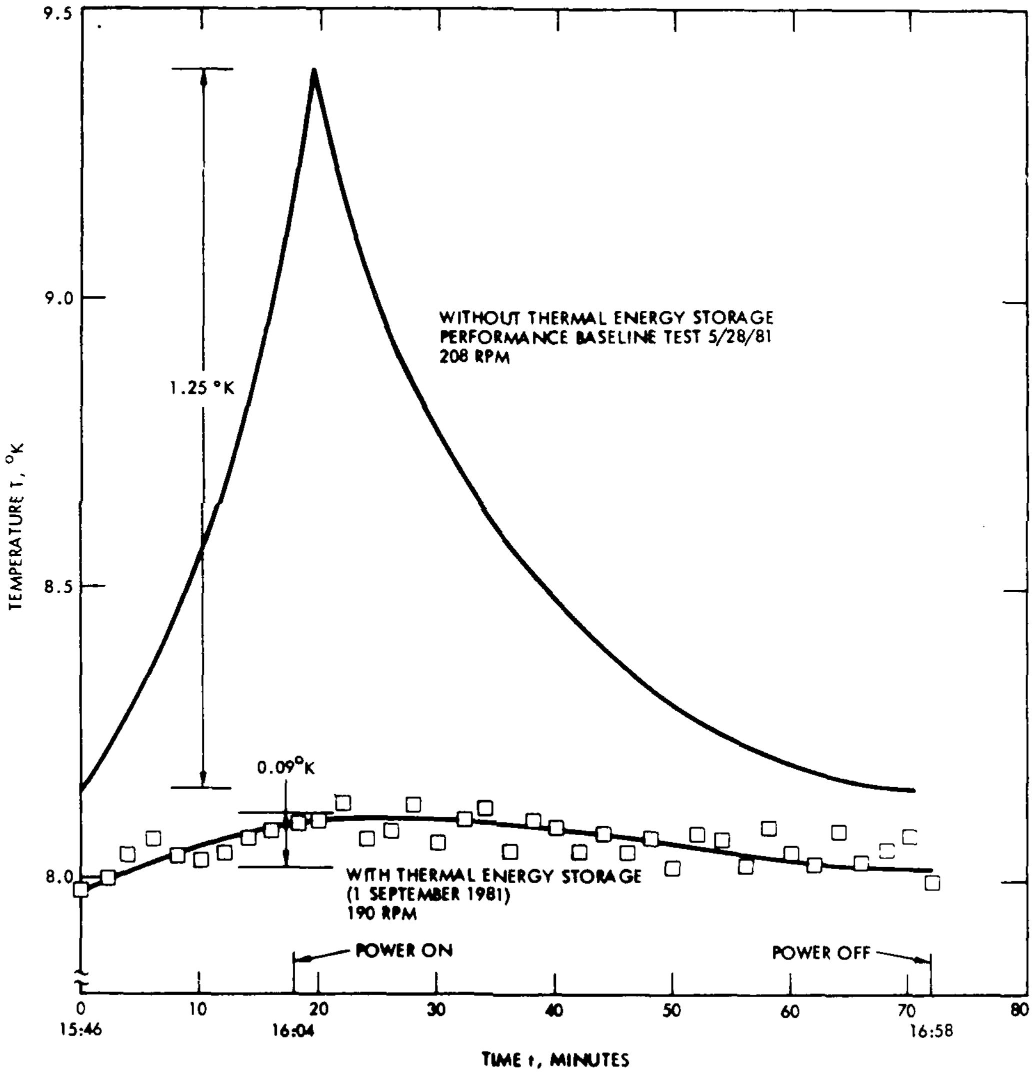

Figure 10 Third Cold Stage Temperature During Discharge and Charge (No Load @ 190 RPM)

of the Vuilleumier cryogenic cooler without a thermal energy storage backup are presented. With the thermal energy storage backup the third stage temperature ranged from a low of 8.02°K to a high of 8.11°K. This compares with a temperature range of 1.25°K for the unsupported Vuilleumier cryogenic cooler operation. Similar results were found for the second and first cold stage, i.e., 0.25°K vs 3.1°K and 0.5°K vs 7.1°K.

Unfortunately, the test did not produce an extended discharge for the no load operating condition of the Vuilleumier Cryogenic cooler.

3.2.2 PARTIAL LOAD AT 190 RPM

The results of the test of the Vuilleumier cryogenic cooler under partial thermal load of the cold stages are quite similar to those which were obtained when the cooler was tested with no load. The temperatures at which the thermal energy storage units achieved full charging conditions were well defined by the change in the temperature - time slope of the temperature as measured by thermocouples #1. This is shown in Figure 11. This test was concluded with an extended discharge which produced several additional data. The total discharge time of the thermal energy storage units was between 20.2 and 20.5 minutes, or an average of 20.35 minutes. This indicates that the total power requirement of the Vuilleumier cryogenic cooler was only P = 1207.37 watt when operating with the TES units, while a power requirement of 1350 watt appears to be indicated when the Vuilleumier cryogenic cooler operated without thermal energy storage backup. The temperatures of the cold stages are presented in Figures 12, 13 and 14. When operating with the thermal energy storage backup the temperature variations are approximately one tenth of those obtained without TES backup. During extended discharge the sensible heat capacity of the TES units contributed considerably to the maintaining of the cold temperatures as is indicated in Figures 15, 16 and 17.

3.2.3 TAC LOAD AT 190 RPM

The results which were generated when the cold stages of the Vuilleumier cryogenic cooler were loaded with TAC loads were very similar to those which were obtained with no load or partial load. The indicated temperature ranges of the hot cylinders during discharge are 37°F and 35°F respectively which is not much different from the temperature variations measured for the two other operating

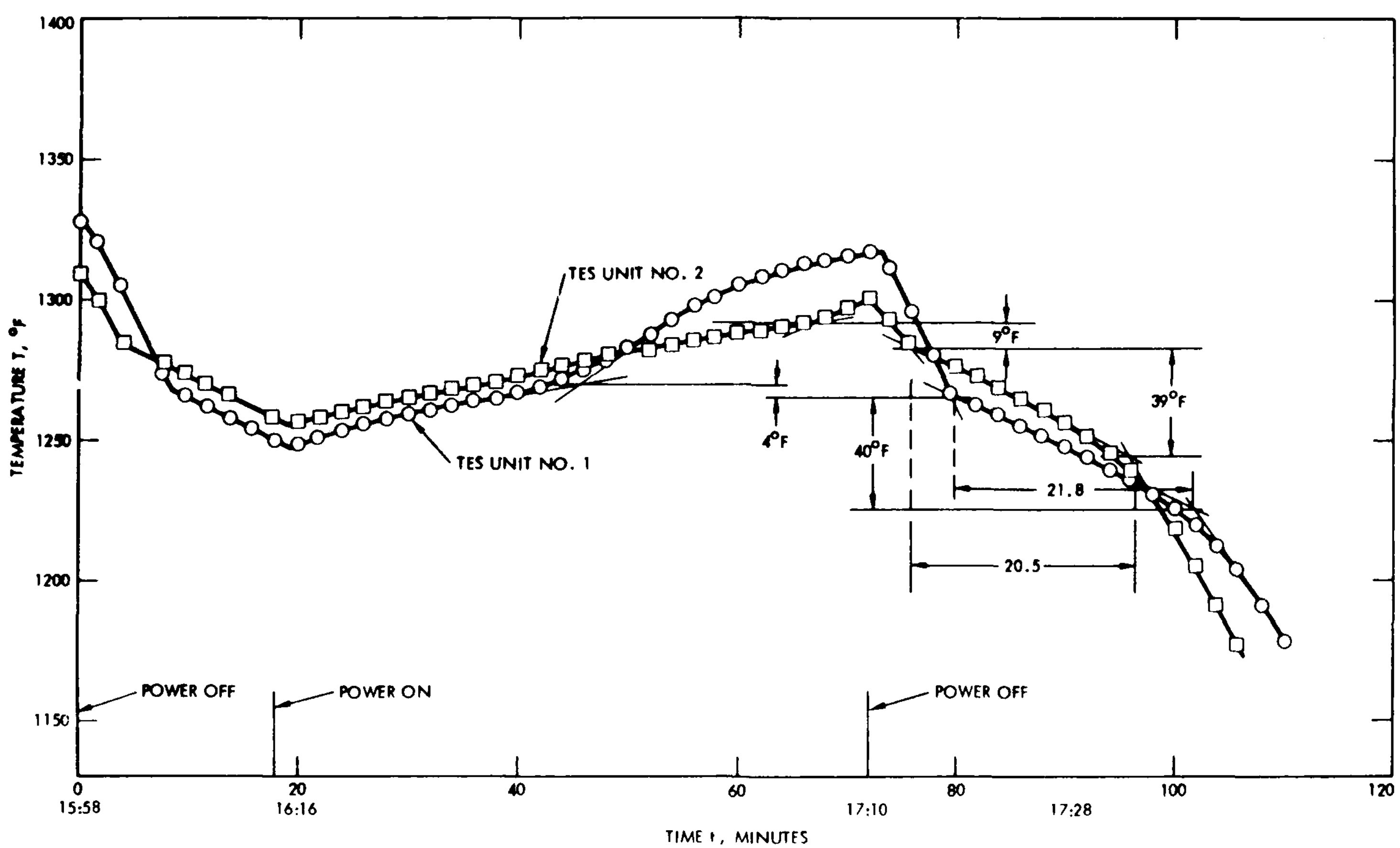

Figure 11 Indicated Hot Cylinder Temperature During Cycling Test (Partial Load @ 190 RPM)

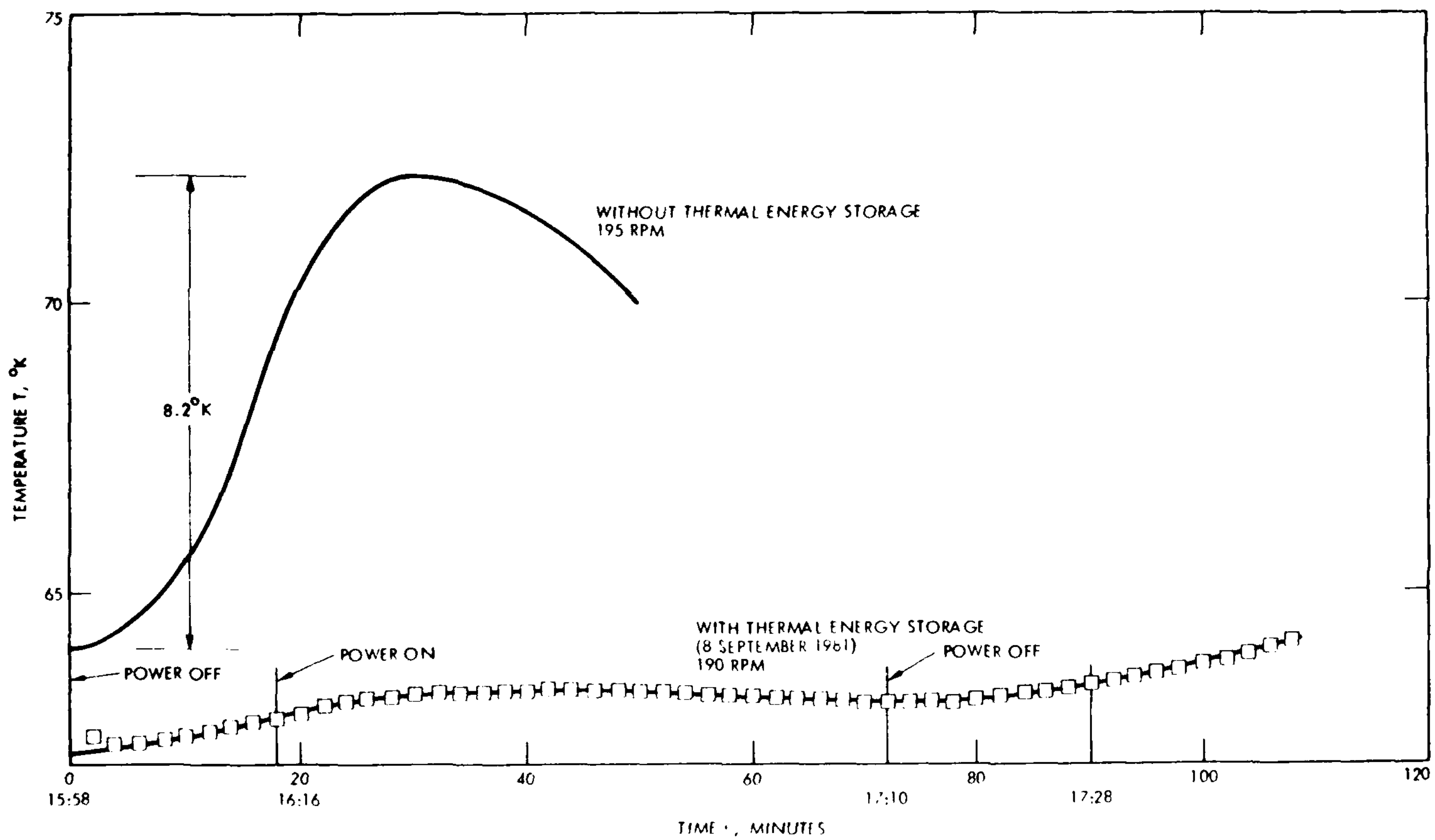

Figure 12 First Cold Stage Temperature During Discharge and Charge (Partial Load @ 190 RPM)

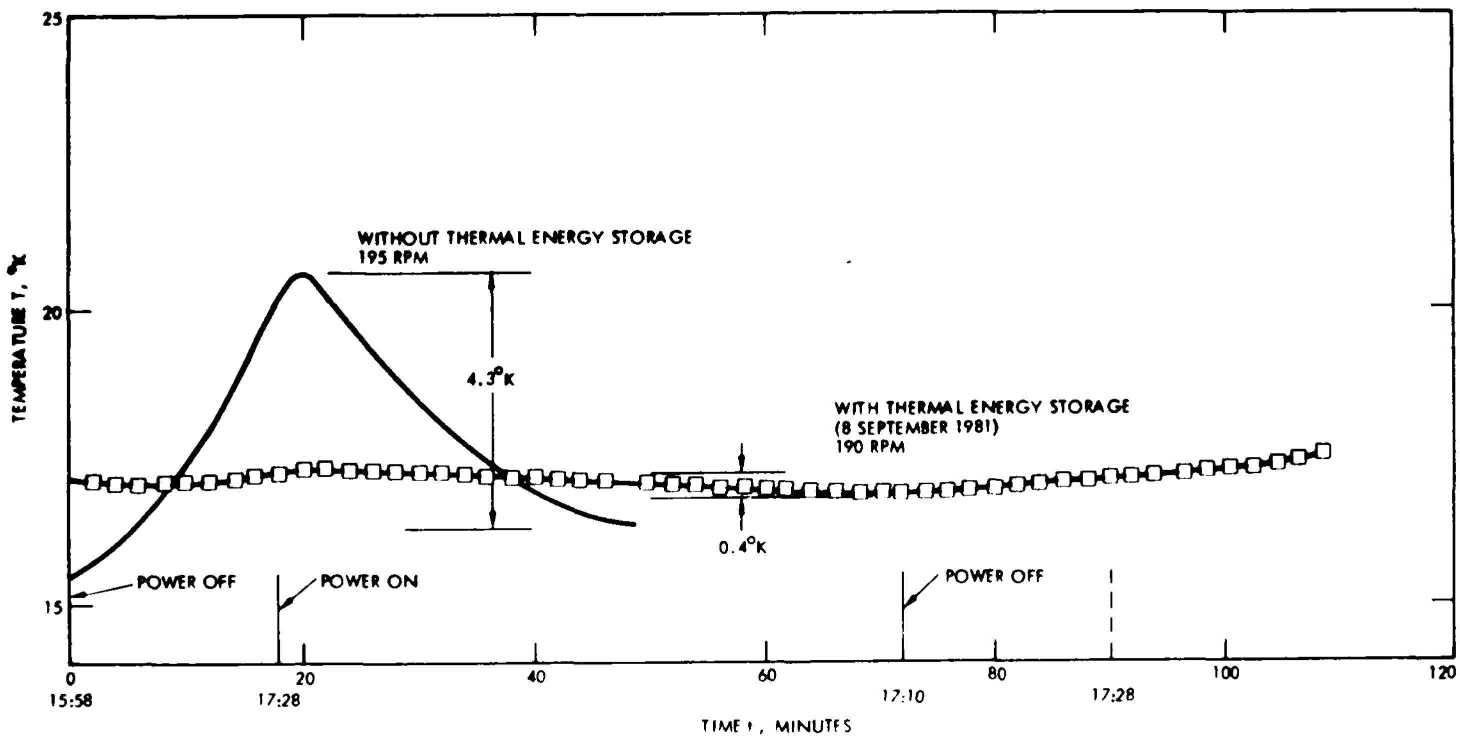

Figure 13 Second Cold Stage Temperature During Discharge and Charge (Partial Load @ 190 RPM)

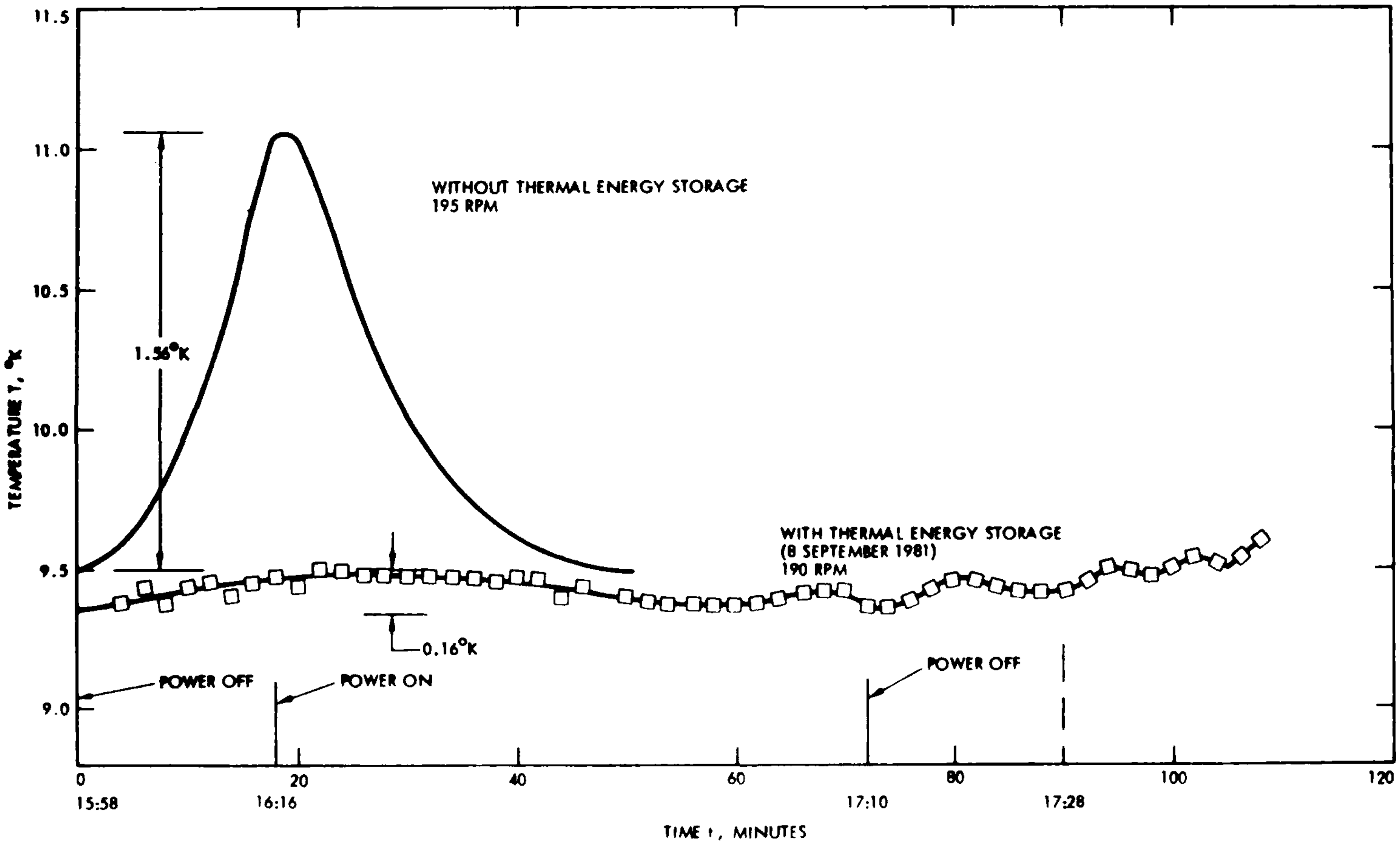

Figure 14 Third Cold Stage Temperature During Discharge and Charge (Partial Load @ 190 RPM)

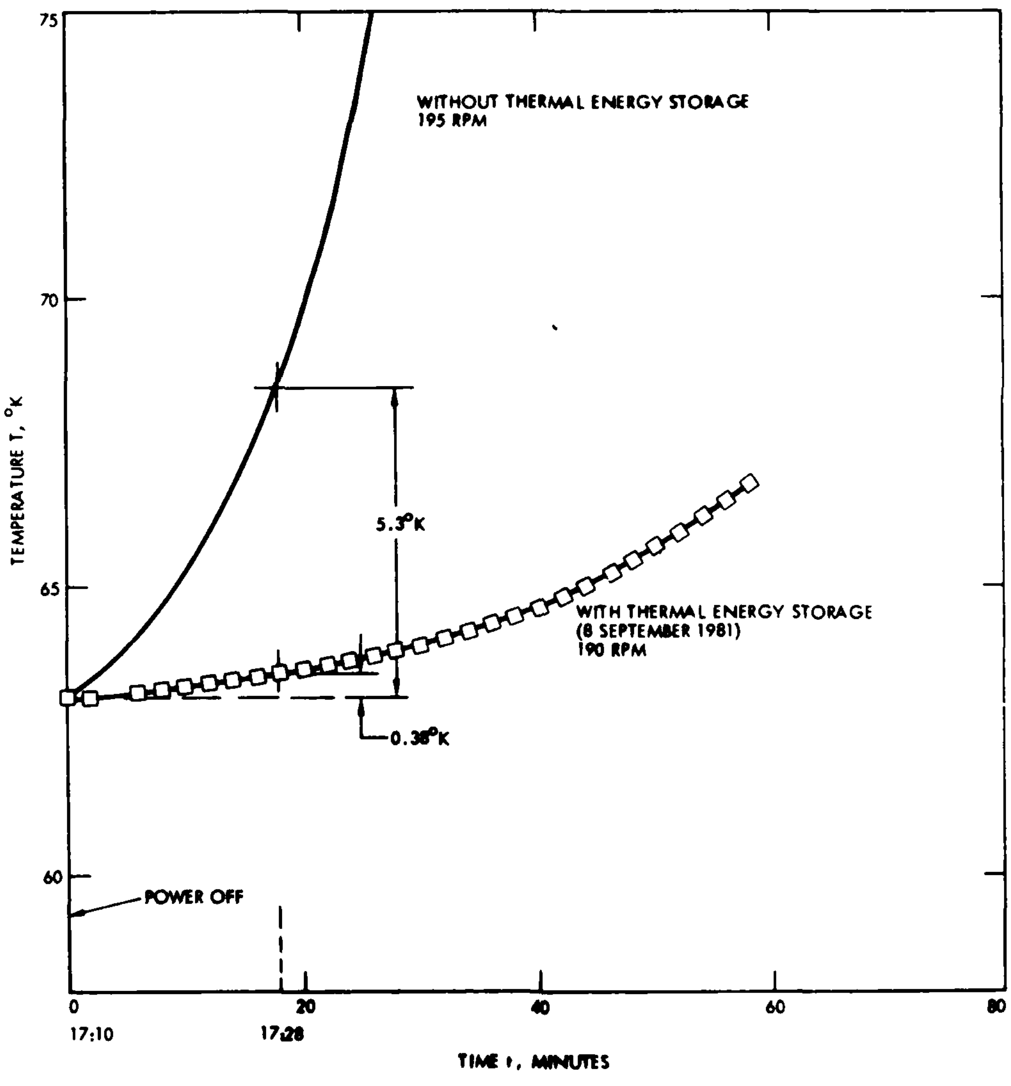

Figure 15 First Cold Stage Temperature During Extended Discharge (Partial Load @ 190 RPM)

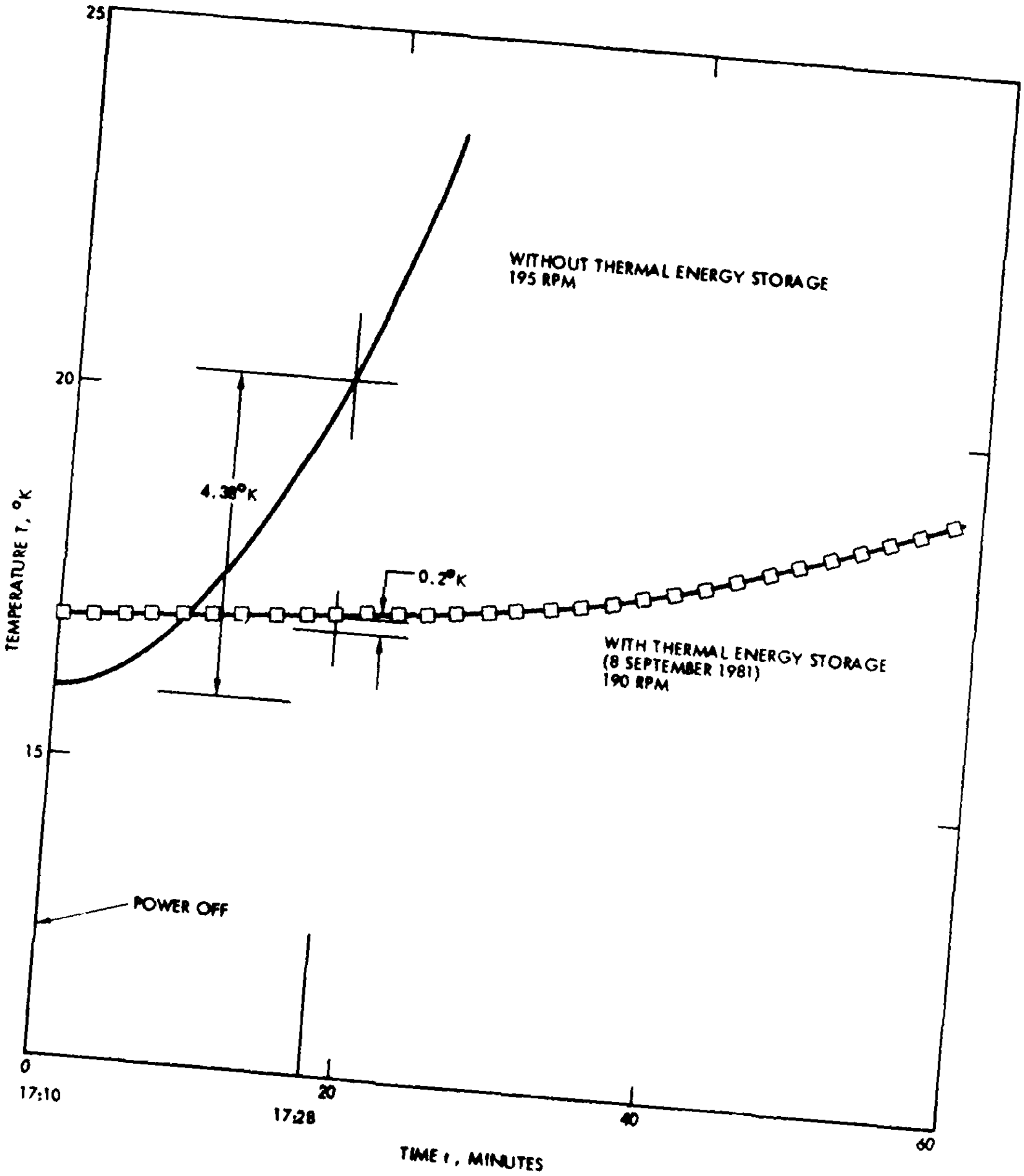

Figure 16 Second Cold Stage Temperature During Extended Discharge (Partial Load @ 190 RPM)

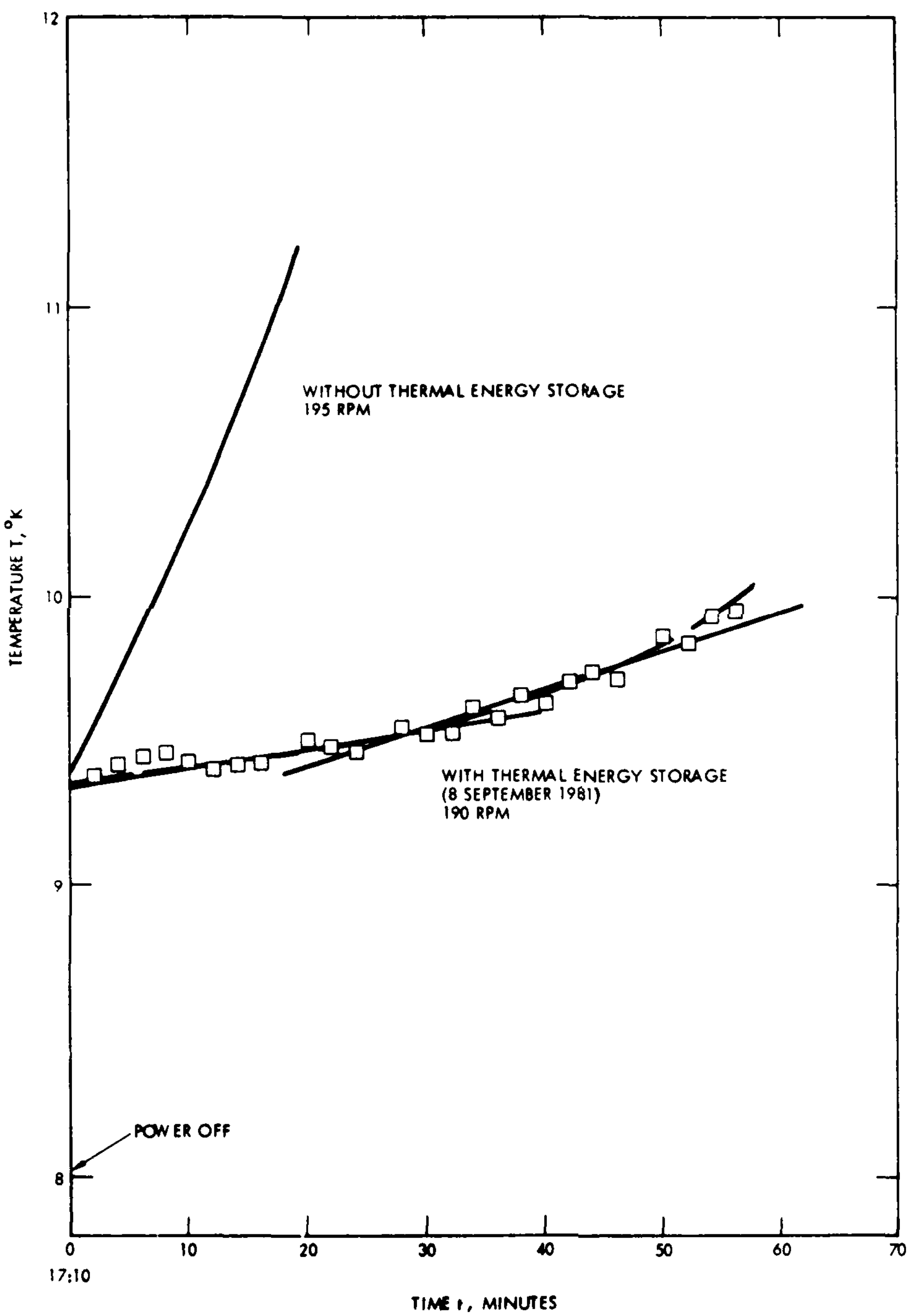

Figure 17 Third Cold Stage Temperature During Extended Discharge (Partial Load @ 190 RPM)

conditions. This presents a good repeatability of the operating conditions for the TES units. The measured hot cylinder temperatures are plotted in Figure 18.

The maximum hot cylinder temperature of unit #2 is considerably lower at the end of the first recharge cycle than in previous tests. Because of the failure of one of the eight heater elements, the average power input during the charging cycle was below the required power input of 910 watt, and the unit did not receive its full charge of latent heat.

The test result is of interest as it confirms that with power control in contrast to temperature control, the temperature band over which the hot cylinder has to operate can be narrowed considerably. The temperatures of the cold stages are plotted in Figures 19, 20 and 21. There appears to be an inconsistency in the temperature of cold stage #2. While the cold temperatures of cold stages #1 and #3 were measured below the temperatures which were indicated in the baseline tests of the Vuilleumier cryogenic cooler, the temperature of cold stage #2 is higher by about 2.5°F. Nevertheless, the range over which the cold temperatures varied during cycling showed the same trend which was found when testing with no load and partial load. The temperature ranges were only about 10% of those which were evident when the cryogenic cooler was operated without TES backup.

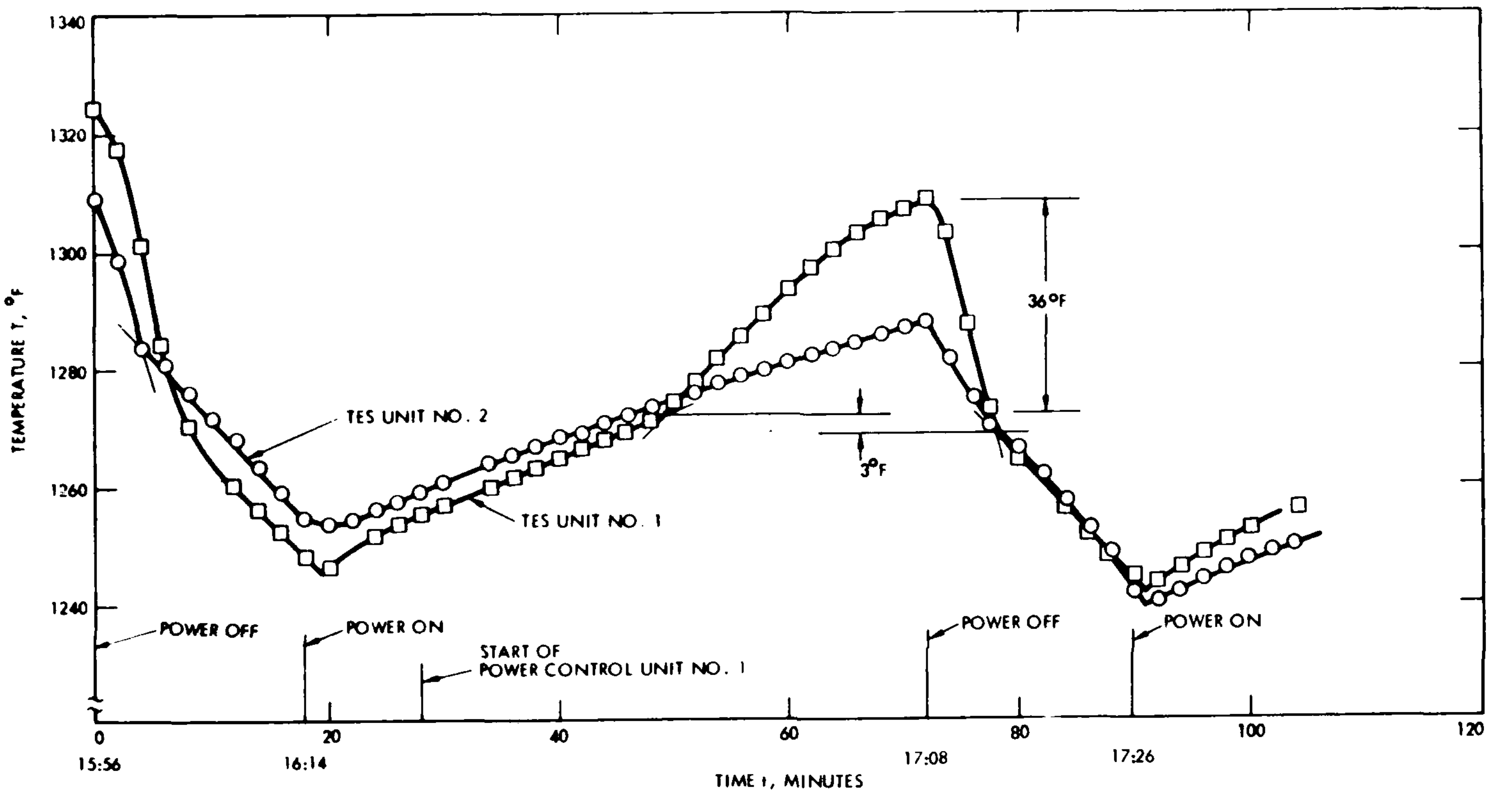

Figure 18 Indicated Hot Cylinder Temperature During Cycling Test (TAC Load @ 190 RPM)

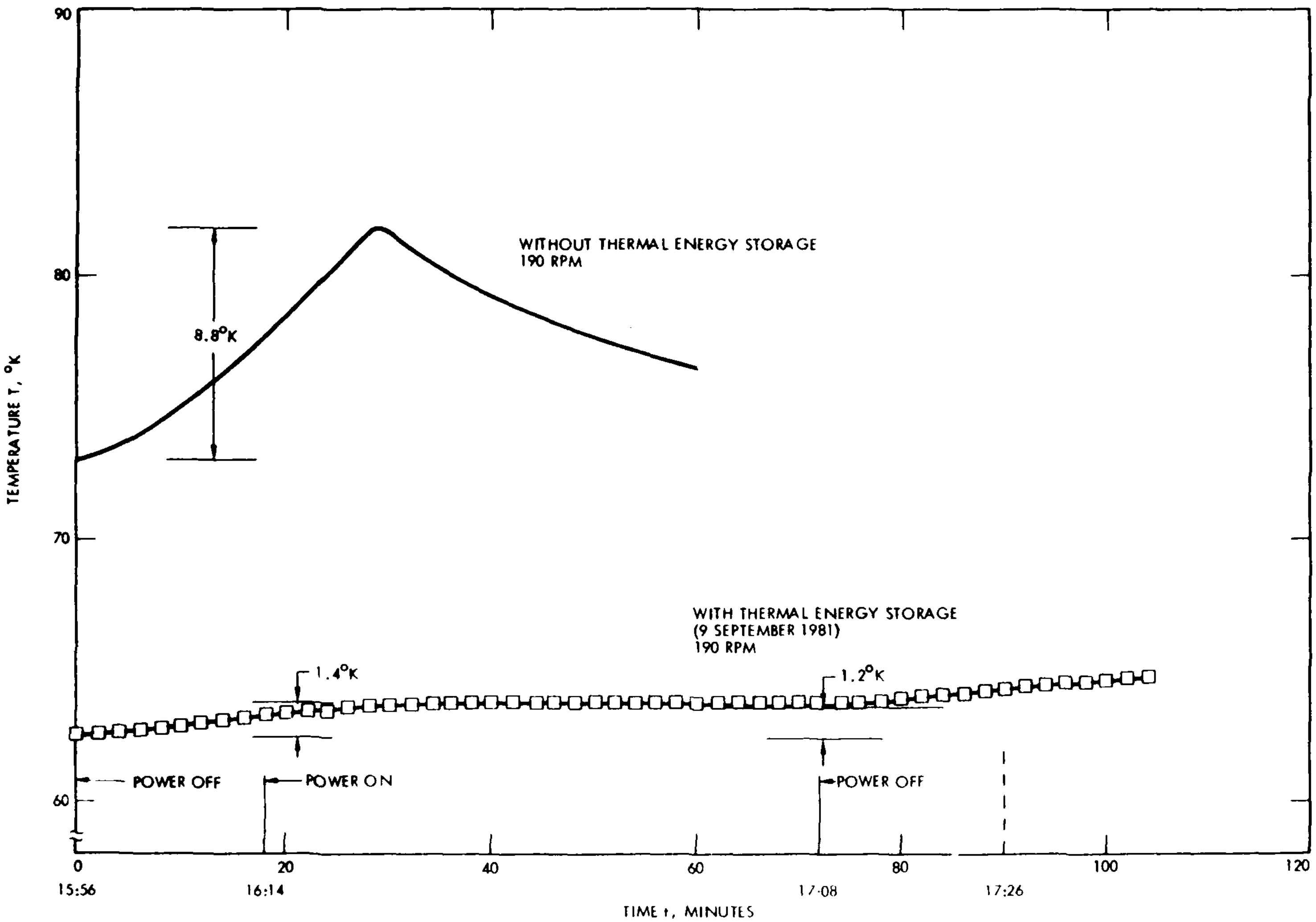

Figure 19 First Cold Stage Temperature During Discharge and Charge (TAC Load @ 190 RPM)

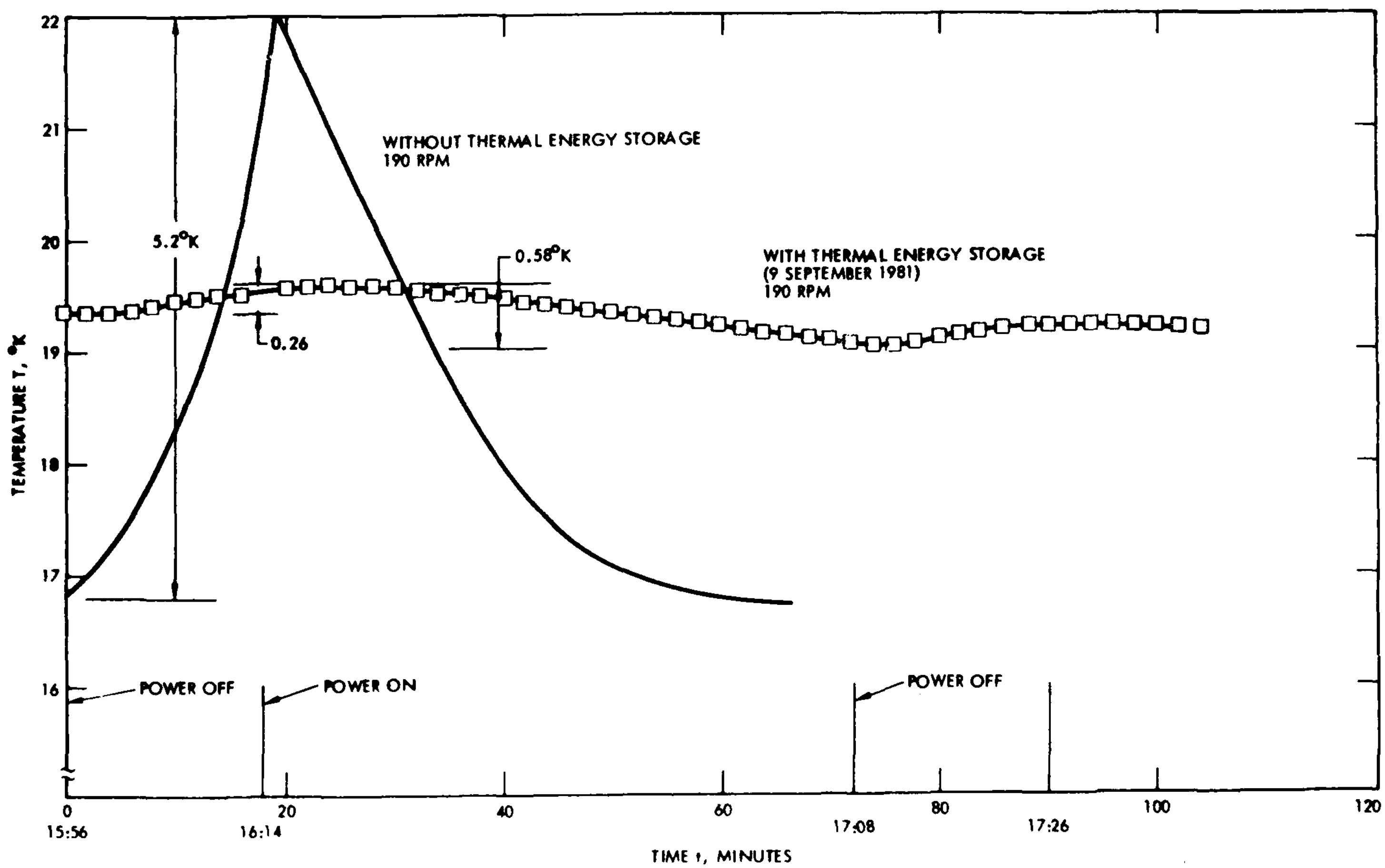

Figure 20 Second Cold Stage Temperature During Discharge and Charge (TAC Load @ 190 RPM)

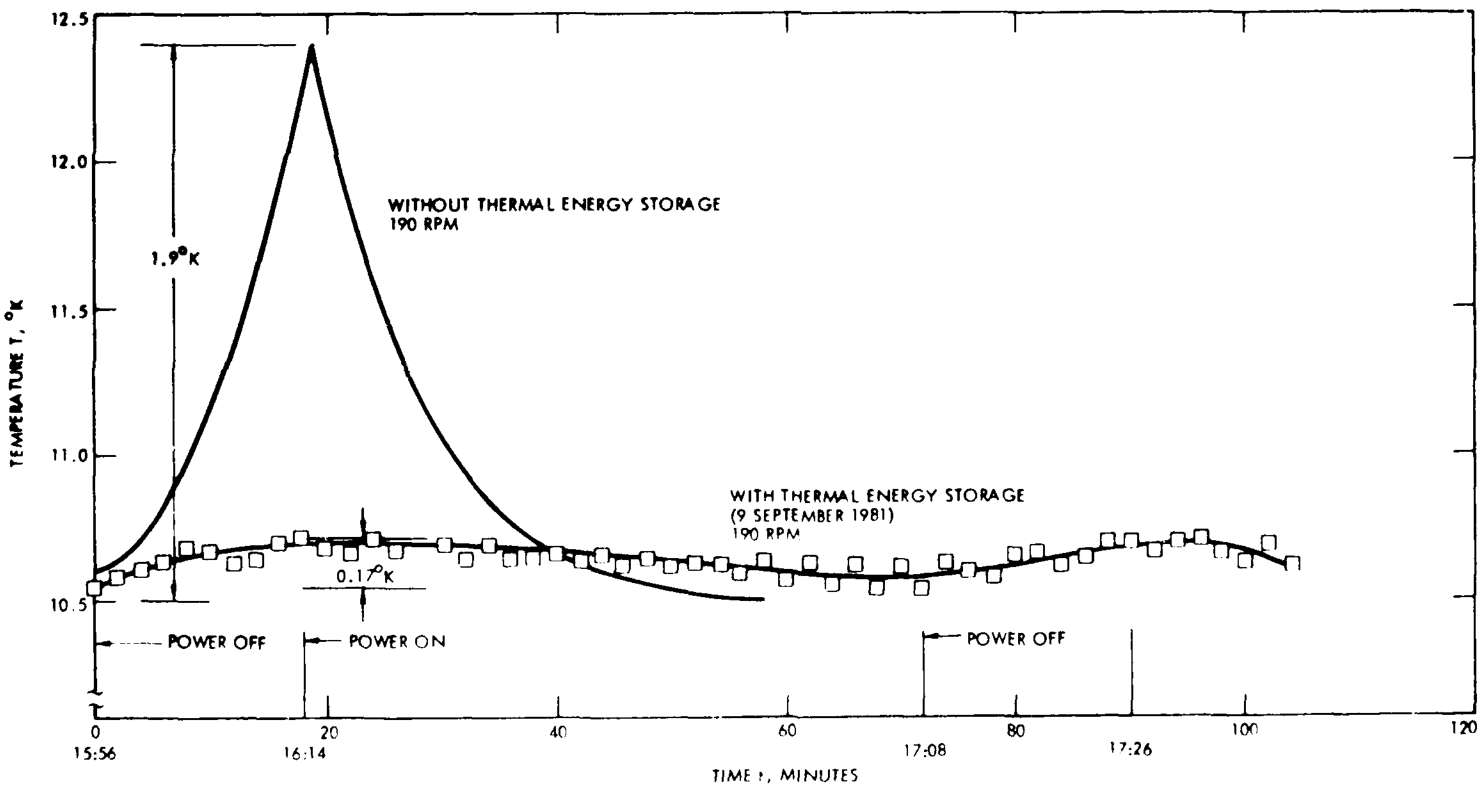

Figure 21 Third Cold Stage Temperature During Discharge and Charge (TAC Load = 190 RPM)

SECTION IV

CONCLUSIONS

The reported test results have proven that thermal energy storage backup of a Vuilleumier cryogenic cooler is a very effective means for maintaining the cold stage temperatures of the cooler within a very narrow temperature range during the time when electrical power is not available for maintaining the hot cylinder temperature.

The time - temperature correlations have shown that the depth of charge of the TES units with latent heat of fusion can be well established by the indicated temperatures. The electrical power input during the charging cycle should therefore occur on two distinct power levels. Initially the total power input should be slightly higher than the requirement for simultaneously operating the Vuilleumier cryogenic cooler and charging the TES units within the charging period. After the temperatures indicate the achievement of the full charge of the TES units, the power input should be reduced to the level which is equal to the Vuilleumier cryogenic cooler demand. With this control logic the temperatures of the cold stages can be maintained within a very narrow band, which will more than satisfy the limits of the sensors.

For achieving full charging of the TES units the upper operating temperatures of the heaters of the TES units had to be raised to 1480°F. The initially predicted temperature of 1360°F had to be exceeded because the actual thermal conductivity of the molten ternary salt proved to be much lower than had been assumed. The test data indicated a thermal conductivity of only k_L = 0.00802 watt/cm-K for the molten TES material. This compares with the thermal conductivity of the solid material of k_S = 0.0297 watt/cm-K, which was assumed to be also the thermal conductivity of the molten material for the initial calculations. Reports had even indicated an increase in the thermal conductivity with phase change of the material.

During the testing a total of four heater elements failed, two in each of the two TES units. One element of TES unit #2 failed during the first recharge cycle, while the other three heater elements failed almost simultaneously during

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he last recharge cycle of this test series. When the TES units were inspected he mode of failure of the heater elements in the two units appeared to differ ubstantially. The two inner elements of unit #1 which are located next to each ther must have failed internally, i.e., opening of the heater wire. The two uter heater elements of unit #2 failed due to a local burnout of the entire eater, sheath and heater wire. The burnout occurred in the section of the eater which penetrates the thermal insulation. From the discoloration of the heath it appeared that the sheath overheated severely. Some of the other heater lements indicated similar overheating of the sheath almost up to the termination leeves. In contrast to this appearance, some heater elements had shiny sheath urfaces for up to 2 inches from the termination sleeve, the appearance of no igh temperature exposure at any time.

he failure mode of the heater elements of TES unit #2 has to be attributed to n incorrect termination of the heater wire in the elements. The heater speci-ication called for a cold length of 2-1/2 inch ±1/4 inch. The heater elements xtended a maximum of 1/2 inch beyond the insulation which has a total thickness f only 1.01 inch. Based on the specified heater element design, the section hich was surrounded by insulation should have remained unheated.

The cause of the failure of the heater elements of TES unit #1 can only be ascertained after the heater elements have been removed from the unit.

Initial computer calculations have indicated that the upper operating tempera-ture of the heaters can be reduced considerably. The heater elements can be laced on the outside of the TES units in such a fashion that only a fraction of the total power input for the hot cylinder is conducted across the thermal energy storage material. The entire temperature history of the hot cylinder during harging remains to be evaluated.

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